

EFFECT OF HYDROREACTION ON THE HYPERVELOCITY PENETRATION

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The contribution of aluminum to air-blast overpressure and underwater bubble size is well known. It is the objective of this work to determine the potential effect of aluminum and other combustible metals and intermetallics on hypervelocity penetration. The work concentrates on underwater behavior taking advantage of its more concentrated oxidative environment versus the more dilute oxygen content in air.

Chemical reaction between hypervelocity aluminum rods and water is evidenced by the luminosity generated during the penetration, localized regions of high temperature thermal emission, the absence of emissions when water is replaced by a hydrocarbon fluid, and the presence of large amounts of alumina product in the rod residue. The limiting contributions of hydroreaction as functions of chemical yield and the time rate of energy coupling dictated by target thickness are estimated, and used as baselines for delineating kinetic and chemical energy contributions.

A model is postulated for estimating the generation of metal reactant during hypervelocity impact and penetration that can be eventually combined with chemical kinetics.

INTRODUCTION

There are indications that aluminum jets react violently during transit through water based on the appearance of intense luminosity, relatively high resultant overpressures and cavity expansion, and detected formation of aluminum oxide. This research is directed towards (1) developing an understanding of the basic mechanisms

that govern the initiation and extent of reaction of aluminum and other combustible metals and (2) determining the potential effect that chemical reaction initiation might have on hypervelocity impact and penetration.

BACKGROUND

Aluminum Reactivity

The exothermic chemical energy released during the combustion of many of Class 5 and transition metals far exceeds that of the most energetic explosive. For example, the detonation energy of HMX is ~1.6 kcal/gram whereas the thermal output from aluminum combustion in air forming the oxide and in water forming the hydroxide or hydrated oxide is ~7.4kcal/gram at STP.

The propensity of aluminum oxidation is well known. The surface of aluminum products are invariably coated with an almost impermeable oxide coating which forms immediately after exposure to air. The blow-out damage to compartmentalized targets impacted by aluminum projectiles is attributed to a cyclic mechanism involving rapid localized atmospheric heating, combustion and thermally-induced particulate fracture that leads to fresh reactive surface creation. The reaction exothermicity is exploited in aluminized explosives for increasing air-blast and underwater bubble size. The influential mechanisms in all of the above cases are dependent on reaction rates of a thousandth of a second and slower.

Evidences of Possible Rapid Underwater Reaction during Hypervelocity Penetration

Indications of possible faster reactions have been observed from intense luminosity within jets and cavities formed during penetration through water media, and the absence of luminosity during penetration through inert fluid media. In water, reaction rates might be faster and more efficient than in air because of the much greater density of water (i.e., three orders of magnitude greater than air), resultant compressional heating and more rapid generation of virgin particulates about the erosion front. Examples of luminous traces during the transit of (1) an aluminum jet from a 25mm shaped charge and (2) a 6.5mm L/D rod launched from a light gas gun through water are shown in Figures 1 and 2, which are qualitatively similar to those observed by Clark and Ciccarelli [1].

Localized thermal emission at combustion temperatures and the appearance, in some cases of AIO emission lines between 430-530nm [2], are indicators of rapid oxidation.

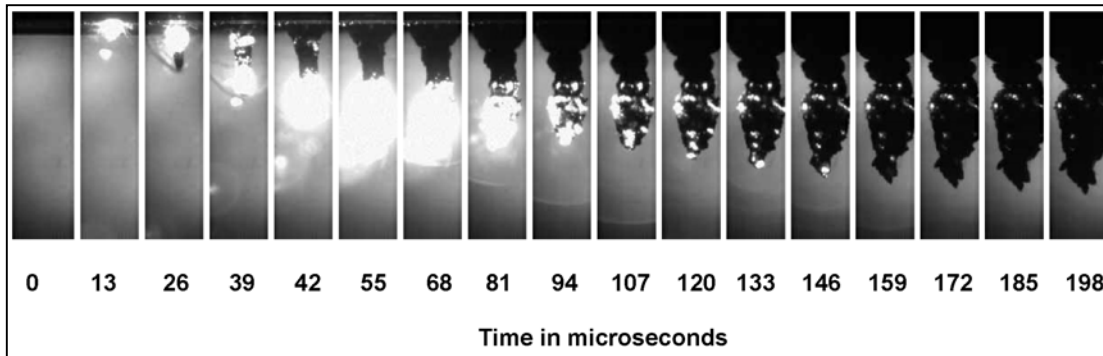


Figure 1: A series of high speed images of an aluminum jet from a 2.5cm-diameter shaped charge penetrating into water (traveling top to bottom) showing enhanced light emission near the liner tip that lasts approximately 100 microseconds.

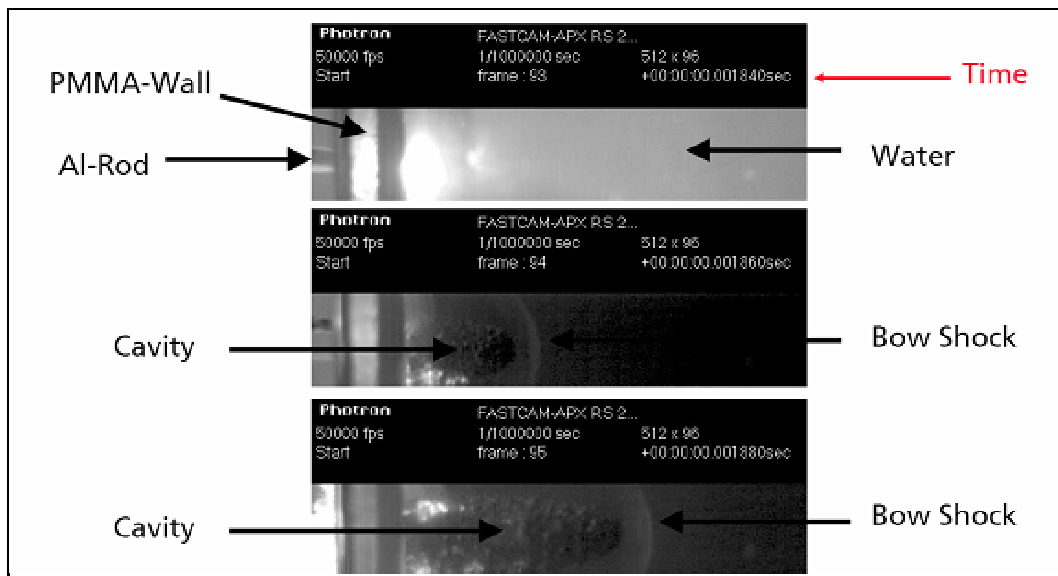


Figure 2. Locations of possible reaction along the erosion interface during the penetration of an aluminum rod through water and the separation of the shock front from the cavity: Impact velocity of the rod is 3.25mm/ μ sec; framing rate is 50,000 frames per second at 1 μ sec exposure time per frame.

Emission spectra within the cavity created in water by aluminum jets from small diameter charges have been fit to grey-body temperatures, and values of 1800 to 3500° K estimated, depending on timing and location, as shown in Figure 3. These spectra were of fairly high signal to noise ratios and were repeatable.

There are indications from previous research [3] that temperatures above 1700°K are required to initiate aluminum combustion in water via a steam explosion mechanism.

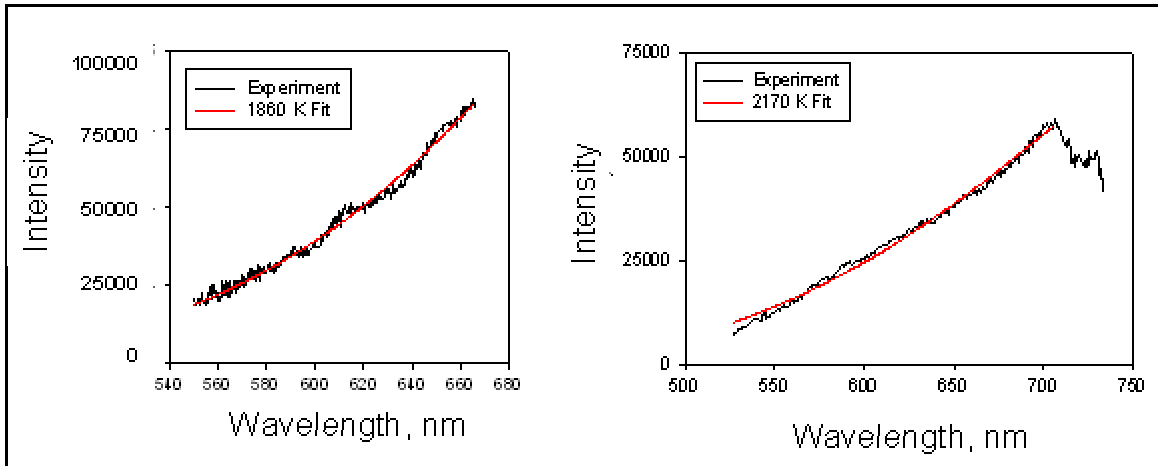


Figure 3. Time resolved spectra from Al shaped charges penetrating into water, and the corresponding grey body spectral fits. Left: fits to 1860°K; Right: fits to 2170°K

Another indication of chemical reaction and energy coupling is observed in a series of tests between small caliber copper and aluminum lined charges of nearly identical design that were performed to determine differences in lateral pressure fields using thin cylindrical containers about the line of sight of the passages of jet flow. Examples of results obtained are reported in Figure 4, where there are shown substantial differences between radial deflections affected by the passage of copper and aluminum jets. Similar results are obtained in finite difference computations where potential chemical energy is simulated by increasing the internal energy of a rod penetrator.

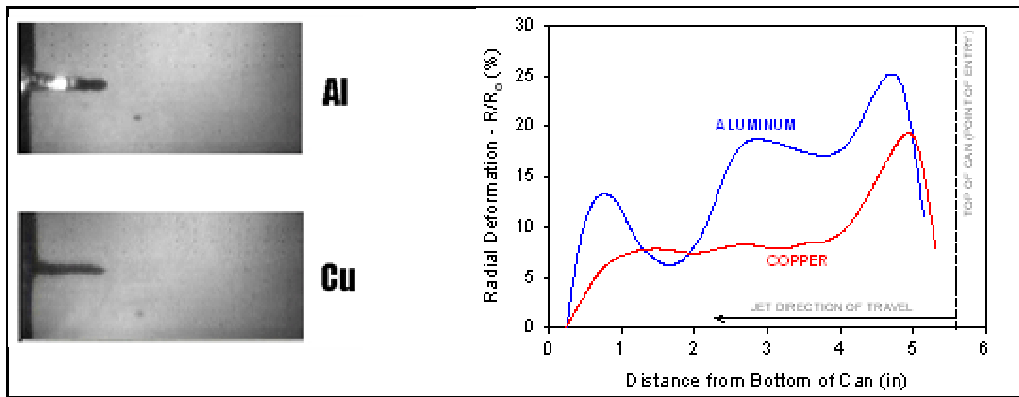


Figure 4. Jets from a RISI RP-4SC EBW detonator containing aluminum (top-left) and copper (bottom-left) and resultant radial deflections of a thin-walled cylindrical water-filled channel through which the jets penetrated.

There are other evidences of aluminum combustion, including particle recoveries from shaped charge jets where there is found almost total conversion of aluminum to γ -alumina based on estimated percent of liner conversion to jet. Of course, any inferences with respect to reaction rate cannot be made from such results.

PROGRESS TOWARD TECHNICAL RESOLUTION

Conditions for Reaction

The essential issue addressed in these studies focuses on determining the importance if any of combustive reaction just prior to and during hypervelocity penetration. Certainly, there is sufficient evidence that reaction occurs; however, in order to generate useful work, it must occur at rates competitive to kinetic energy exchange, if not faster. It is assumed that thermal mechanisms leading to structural softening might be important, similar to that identified during shaped charge impact by Prentice and Curtis [4].

The elevation of internal energy about the front of a 4 km/sec aluminum rod impacting into a submerged aluminum target is estimated to result in partial rod vaporization. This estimate based on AUTODYN Lagrangian computations, which were experimentally validated against Southwest Research Institute data [5], suggests that conditions at these impact conditions might indeed support rapid reaction. Bow shock-wave energy and elevated internal energy from reaction may also pre-impact weaken thin targets and lead to hole expansion, again under conditions where energy coupling occurs in microseconds.

Reaction Model

A postulated reactive surface generation scheme presented herein provides a possible basis for constructing a kinetic-chemical theory ultimately capable of identifying and quantifying chemical energy release mechanisms during pre-impact to terminal penetration of reactive penetrators.

It would appear that the creation of fresh surface is the efficient path through which the hydroreaction of a hypervelocity aluminum jet-rod can occur. The normal thin oxide coating on aluminum slows down, or can eliminate, further reaction. Thus, the premise is that the only reaction pathway that can possibly compete with penetration is by way of interactions at the aluminum-water erosion front. It is shown in the following argument that the rate of fresh surface exposure should be as fast as the penetration process. The only question is whether the surface and depth to which water can react is

sufficient to release enough energy to affect perforation. In any event, added energy in the penetrator bow resulting from reaction might effectively add to lateral effects.

The hypervelocity penetration through fluids generally follows hydrodynamic theory with the exception that the strength of the penetrator cannot be ignored [6]. In this case the expanded form of the Tate-Eichelberger hydrodynamic penetration equation is used,

$$\frac{1}{2} \rho_p \cdot (v-u)^2 + \sigma_p = \frac{1}{2} \rho_t \cdot u^2 \quad (1)$$

$$u = \frac{\left[v^2 - (1-\gamma^2) \cdot \left(v^2 + 2 \cdot \frac{\sigma_p}{\rho_t} \right) \right]^{1/2}}{(1-\gamma^2)} \quad (2)$$

where, ρ and σ are density and strength properties and subscripts p and t denote properties of the penetrator and target respectively, γ is the ratio of target to penetrator density, v is the impact velocity and u is the penetration velocity.

The rate of rod erosion normalized by the penetration velocity, $(v-u)/u$, represents the length of rod eroded per unit penetration, where the initial rod length is l_p . i.e.,

$$\frac{(v-u)}{u} = - \frac{d l_p}{d P} = \frac{\Delta l_p}{P} \quad (3)$$

Allen and Rodgers [7] show for the case of an impacting rod of much higher density than the target, the eroded material can add to secondary penetration: Inertial effects setup prior to the complete erosion of the penetrator are usually considered to be the cause of secondary penetration. The specific example, reported by Allen and Rodgers is a gold rod impacting into aluminum. They point out that the speed of a free streamline is not affected by a change in direction, and thus the velocity of reflected material at the bottom of a crater is the negative of the velocity of the penetration front, i.e., $(u-v)$. In the coordinate system of the target the residual velocity, v_r , of the reflected material from the eroding penetrator is $2u-v$ (see Figure 7).

Allen and Rodgers derived an equation that relates the rate of secondary penetration, v_r , contributed by the forward motion of eroded material after complete penetrator depletion. This expression is shown in the following equation:

$$v_r = \frac{2 \left[\rho_p^2 \cdot v^2 - 2 \cdot (\rho_t - \rho_p) \cdot (\sigma - \rho_p \cdot v^2) \right]^{1/2} - (\rho_t + \rho_p) \cdot v}{(\rho_t - \rho_p)} \quad (4)$$

For the case where the residual velocity, v_r , greatly exceeds the flow strength of the target, which is certainly true for the cases under study, the penetration velocity is governed approximately by hydrodynamic theory.

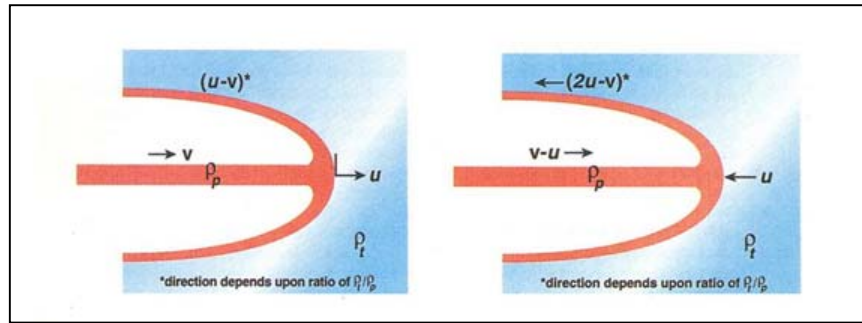


Figure 7. Schematic of the penetration process and reverse erosion streamline in (a) the laboratory frame and (b) in the steady-state reference frame: Taken from [8].

The diameter of the streamline (or hole, d_h) can be approximated by conservation of energy, taking into account the effect of thermal softening; in which case material response relationships such as Johnson-Cook can be invoked. The expression below equates the total useful energy available for hole expansion. k is the chemical reaction efficiency, $\sigma(T)$ is the temperature dependent strength of the target and V_h is the target hole, which contains the penetration depth,

$$\sum((KE) + k(CE))_p = \sigma(T) \cdot V_h \quad (5)$$

Since the penetrator is eroded at $(v-u)$ and the rate of eroded penetrator debris is increasing at the same rate, the sum of the length of debris is

$$\begin{aligned} \ell_d &= \ell_p - \ell \\ \ell_d + \ell &= \ell_p \end{aligned} \quad (6a, 6b)$$

where, ℓ_p the initial penetrator length. Similarly, the penetrator mass is equal to the sum of the mass remaining in the penetrator and eroded mass, at any given time. The thickness of eroding material in the reverse streamline is directly related to the rate of stretch, the crater diameter, i.e., interfacial diameter along the target crater and the erosion-streamline, and the rate of penetrator mass conversion to eroded mass, i.e.,

$$\frac{dm}{dt} = \frac{\rho_p \cdot d_p^2 \cdot \pi \cdot (v-u)}{4} \quad (7)$$

The rate of exothermic energy released by a combustible penetrator should, therefore, be governed by this rate of mass erosion and the resultant fraction this is directly exposed to an oxidizing media (1st step). Reaction at sub-layers below the surface (2nd step) is dependent on the rate of oxidizer diffusion through the initially formed surface oxide layer.

CONCLUSIONS

The reaction of aluminum with water during hypervelocity penetration has been confirmed by a variety of means including spectroscopy and the quantification of the conversion of metal to oxide in the residue. The combustion is characterized by intense luminosity in the form of high temperature thermal emission, and in some cases, molecular AlO emission. In addition, the pressure impulse in the water is enhanced, resulting in greater pressure-induced target deformation. A model is postulated to quantify the generation of reactive material during hydrodynamic penetration. The model, when combined with surface and subsurface diffusion-controlled chemical kinetics, should be useful in quantifying the rate of thermochemical yield during the hypervelocity impact and penetration through water and into submerged targets.

ACKNOWLEDGEMENT

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REFERENCES

- [1] R. Ciccarelli and R. Clark, private discussions.
- [2] T. Bazyn, H. Krier, and N. Glumac, "Oxidizer and Pressure Effects on the Combustion of 10-micron Aluminum Particles," *Journal of Propulsion and Power*, 21, 577-582, (2005).
- [3] M. Epstein, H. K. Fauske, T. G. Theofanous, "On the Mechanism of Aluminum Ignition in Steam Explosions," *Nuclear Engineering and Design*, 201, 71 (2000).
- [4] H. Prentice and J.P. Curtis, "Heat Generation by Shaped Charge Jet Penetration", *Int'l J. Impact Engineering*, 29, 589 (2003).
- [5] C.E. Anderson, B.L. Morris and D.L. Littlefield, "A Penetration Mechanics Database", Southwest Research Institute, SwRI Report 3593/001 (Jjan 1992).
- [6] C.E. Anderson Jr., J.S. Wilbeck., and J.S. Elder., "Long-Rod Penetration into Highly Oblique, Water-Filled Targets", *Int'l J. Impact Engng.*, 21, 1,(1999).
- [7] W.A. Allen, and J.W. Rogers, J.W., "Penetration of a Rod into a Semi-Infinite Target", *J. Franklin Institute*, 272, 275 (1961).
- [8] D.L. Orphal., and C.E. Anderson Jr, "Streamline Reversal in Hypervelocity Penetration", *Int'l J. Impact Engng*, 23, 699 (1999).